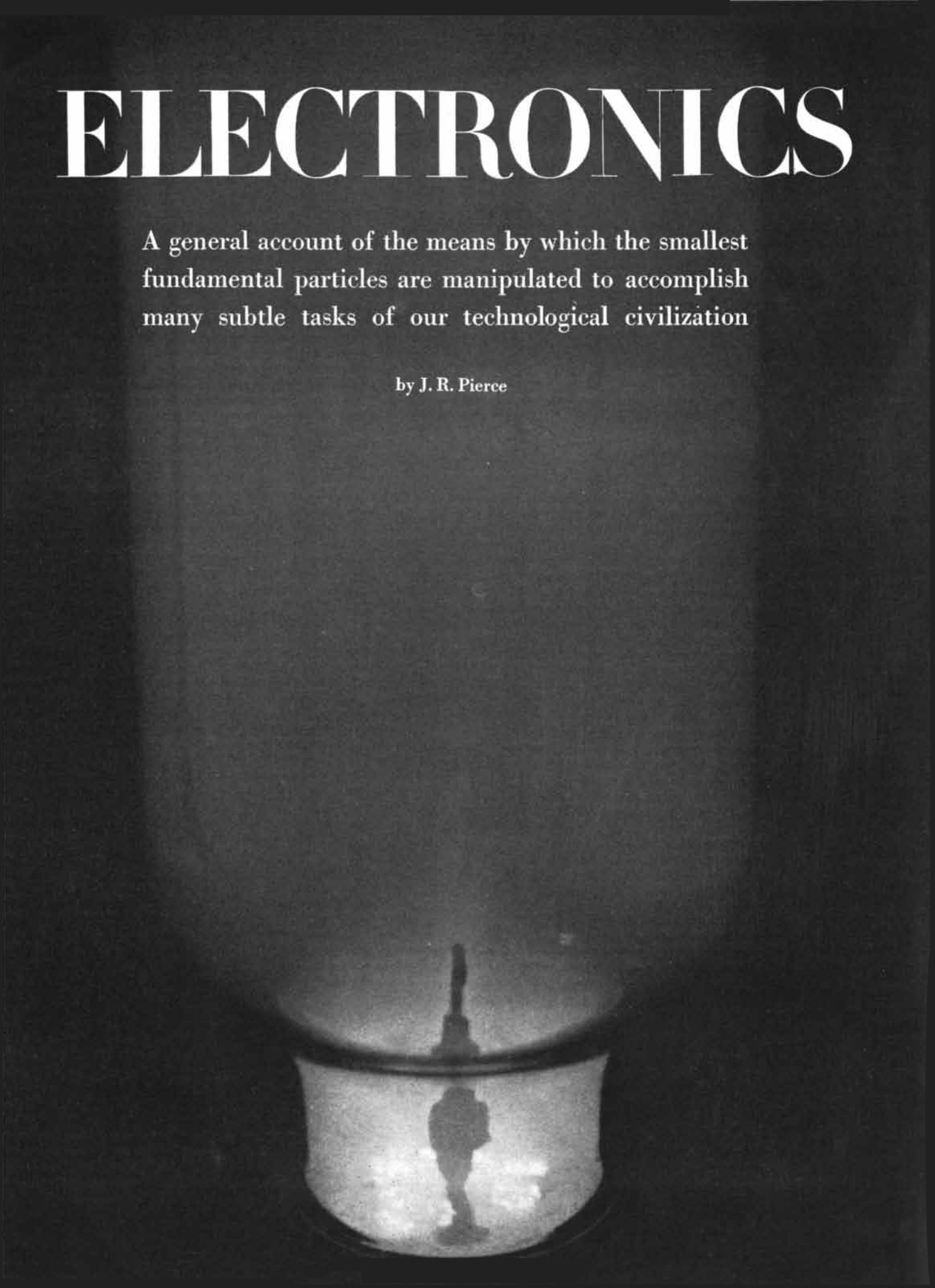
ELECTRONICS

A general account of the means by which the smallest fundamental particles are manipulated to accomplish many subtle tasks of our technological civilization

by J. R. Pierce



MODERN technology is made possible by some understanding of basic scientific laws or principles. Sometimes this understanding has come in the train of practical application; for instance, thermodynamics was strongly inspired by the empirical invention of the steam engine. In later times this order has come to be reversed. The most recent important contribution of physics to technology, the atomic bomb, is the outgrowth of long years of patient unraveling of nuclear physics; it would never have been made through mere garret inventing.

The development of electronics has combined both of these prods to progress; its scientific foundations and its applications have been closely intertwined, and each has inspired the other. To explain the electron tube as the outgrowth of years of science for its own sake would be to underestimate the importance of such a contribution of genius as Lee de Forest's invention of the audion, on which all our television, radio and long-distance telephony depend. On the other hand, much of our present detailed understanding of applied electronics has grown out of more basic studies, some aspects of which were available long before de Forest hit upon his invaluable invention without, perhaps, fully understanding its operation.

Electronics deals with the behavior of minute particles of electricity called electrons. The name actually came before the thing, for in 1858 William C. Richards wrote an epic poem in which he ascribed the wonders of electric telegraphy to a sprite he named *Electron*. It was not until 1891 that the British physicist G. Johnstone Stoney used the word electron in its modern sense to describe a fundamental particle of electricity, and not until 1897 that his fellow countryman Joseph John Thomson demonstrated the electron's existence.

The idea that electricity consists of little units goes back to that versatile British experimenter and theorizer Michael Faraday. But Faraday was concerned with the flow of electricity in liquids or solids, and electronics could not be born until men began to study electricity moving freely in space, that is, the motion of electrons in a vacuum. It was through the study of electrical discharges in crudely evacuated glass tubes that the effects of the electron were first detected and studied.

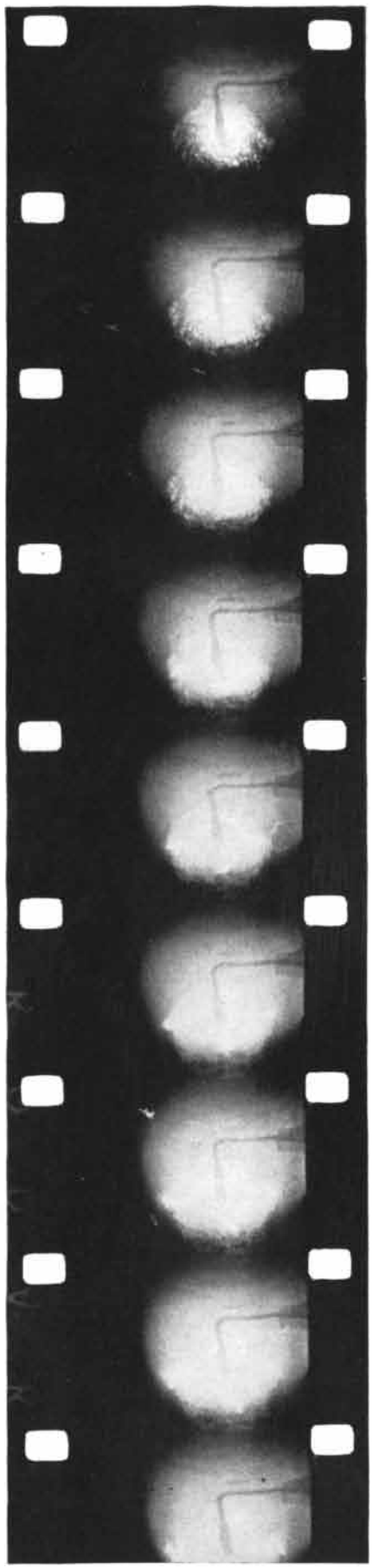
Geissler's Tube

We may well start with Heinrich Geissler (1814-1879), an itinerant German glass blower turned physicist who settled at the University of Bonn, where he was eventually awarded an honorary doctorate. Geissler was interested in vacuum pumps as well as in glass-blowing, and he made some improved pumps for extracting the air from his long, oddly shaped glass tubes. He discovered that when a high voltage was applied between two electrodes he had sealed in the ends of a tube, the rarefied gas in the tube glowed brightly.

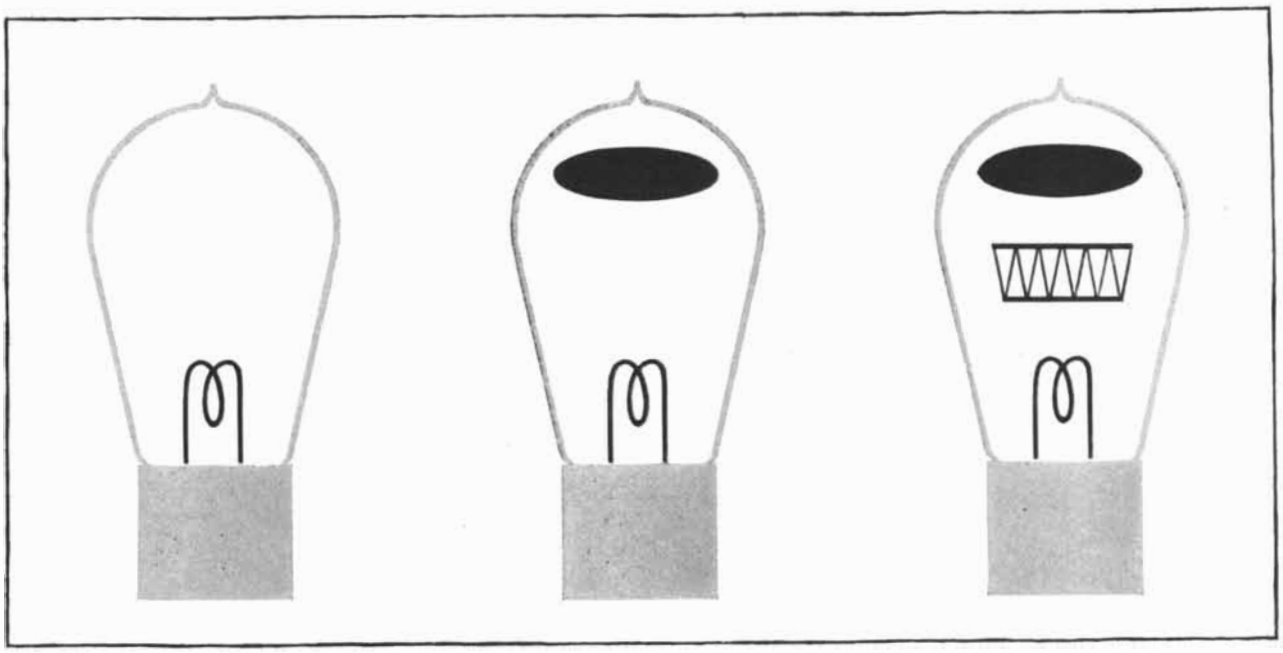
Geissler's tube was the ancestor of our neon signs. But Geissler did not understand the reason for the gas discharge in his tubes. Others began to explore this mystery, and among them was the indefatigable and ingenious experimenter Sir William Crookes. Starting about 1878, Sir William made several experiments with glass tubes similar to Geissler's but shorter and stubbier. As he pumped the air from his tubes, Crookes saw the same glow Geissler had observed. He noticed, however, that as the pumps worked longer and a higher vacuum was obtained, the glow became fainter and finally almost vanished. But now the glass wall of the tube opposite the negative electrode shone softly. Crookes realized that something—gas, particles, rays or whatever—was striking the glass.

To investigate this he put little metal obstacles in his tube. They cast a sharp shadow on the wall opposite the negative electrode. Crookes now knew that the something he was dealing with traveled in straight lines. He then placed a little metal paddle wheel in the path of this stream of something. The paddle wheel turned when the beam struck it. Crookes decided that the mysterious agent whose impact turned the paddle wheel must be a stream of tiny particles. He called this luminous, tenuous stream of particles a "fourth state of matter"—neither solid, liquid nor gas but something finer than any of them.

The curious thing is that he was right about the existence of a stream of par-



IGNITRON is a modern electronic tube in which the electrons flow from hot spots on a pool of mercury through a gas to a positively-charged electrode. In the photograph on the opposite page the mercury pool and its igniter electrode are at the bottom. The positive electrode is out of the picture at the top. This photograph and the strip at the right, which was made at 2,000 frames per second, were undertaken by H. W. Lord of the General Electric Company to analyze the behavior of the hot spots. Studies of pictures of this kind indicate that under certain conditions the spots attain a velocity of 40 feet per second. They also indicate that as the current flowing through the tube increases, the spots divide at currents averaging 15 amperes per spot. As the current decreases, spots die at currents averaging five amperes.



THREE BASIC ELEMENTS of electronic tubes are cathode, anode and grid. The cathode is a negatively-charged electrode which emits electrons. The anode is a positively-charged electrode which attracts electrons. The grid controls the flow of electrons from cathode to anode. Tube at left contains a simple cathode. Tube in center, containing cathode and anode, is a diode. Tube at right, containing cathode, anode and grid, is a triode.

ticles but incorrect in deducing them from the turning of the wheel. Twenty years later Thomson showed that whatever caused the paddle wheel to turn, it was surely not the impact of charged particles!

Crookes caused the stream of particles in his tubes to strike various substances and found that some of them glowed much more brightly than glass. (In modern television tubes the substances that glow so brightly when a stream of electrons strikes them are phosphors.) Crookes also found that a magnet could bend and twist the stream of particles, but apparently he did not understand what he saw.

In 1895 Jean Perrin, a French investigator, correctly deduced what the deflection of Crookes' stream of particles by a magnetic field meant. Uncharged particles, such as molecules of gas, would not be deflected, but charged particles in motion in a magnetic field would. Most important, the direction of deflection would depend on whether the charge was positive or negative and on the direction of motion with relation to the magnetic field. Perrin knew the direction of motion and the orientation of the magnetic field; from this he was able to determine that the particles' charge was negative. Crookes' "fourth state of matter" had been identified as a moving cloud of negatively-charged particles.

Were all the particles in the cloud of the same type? In 1897 Thomson began to investigate their nature. He cut the cloud of charged particles down to a well-defined beam by passing them through two lined-up apertures, and to this stream he applied both an electric and a magnetic field.

Now the two kinds of field act on a charged particle in different ways. An electric field, created by a voltage between two sheets of metal, urges a negative particle toward the positive electrode whether the particle is moving or not. The electric force involved in the particle's attraction toward the electrode is proportional to the charge on the particle times the strength of the electric field. A magnetic field, on the other hand, exerts a force on a charged particle only if the particle moves across the magnetic lines of force. Hence the speed of the particle now enters the calculation; the force deflecting it is proportional to the speed of the particle times the charge on the particle times the strength of the magnetic field. When either a magnetic or an electric field bends the path of a particle, the amount of bending varies inversely as the mass of the particle.

Thomson applied these facts to measure the physical properties of the particles. He first measured the deflection caused by a magnetic field of known strength. Since he knew the strength of the field, he was able to calculate the relation between the particle speed and the ratio of the charge of the particles to their mass. He then balanced the deflecting effect of the magnetic field by an electric field. This additional information told him the velocity of the particles. He could then calculate the ratio of charge to mass for the particles; that is, how much electricity they carried per pound. He found that this ratio of charge to mass was the same for all the particles, and that the particles were remarkably light. They were much electricity and little matter.

Although Thomson's experiment showed that these new particles, now called electrons, were very much alike, it was not yet demonstrated that they were all the same. To do this, it was necessary to measure the charge carried by the particles, and this was done in a number of ways. The most decisive was a series of experiments begun in 1909 by Robert A. Millikan, then at the University of Chicago. He caught electrons by ones, twos and threes on tiny drops of oil and measured the forces exerted on them by an electric field. Millikan's experiments showed conclusively that all electrons have exactly the same charge. Clearly all electrons must also have the same mass, for Thomson had shown that all electrons have the same ratio of charge to mass.

The experiments in bending the path of electrons suggested an interesting question. If magnetic and electric fields could deflect streams of electrons, was it possible that such fields might also focus an electron stream, as lenses focus a beam of light? By 1926 the German physicist H. Busch had proved that this was indeed the case. He showed that all symmetrical electric and magnetic fields act on streams of electrons much as lenses act on rays of light, and electron optics was born. From it has come such a great tool as the electron microscope.

But we are concerned here principally with the electron tube. The first

question we must consider is the source of electrons. There are several ways in which an electron can be released from matter. In a gas-discharge tube the process by which electrons are knocked out of the negative electrode is very complicated and roundabout. The free, moving electrons in the tube run into molecules or atoms of gas. When the collision is sufficiently violent, an electron may be knocked out of the molecule, which is thereby left with a net positive charge. This positive ion is attracted toward the negative electrode of the tube. On finally striking that electrode, it can knock one or more electrons out of the metal.

Electrons can be knocked out of a metal or other substance by electrons as well as by positive ions. This is called secondary emission, the "secondary" electrons being the electrons knocked out, as distinguished from the primary electrons which do the knocking. One primary electron may produce several secondary electrons. This process is of great technological importance. Equally important is the release of electrons by radiation such as light or X-rays, a phenomenon called photoelectric emission and employed in the photoelectric cell.

But the form of electron release that has perhaps the greatest technological importance is thermionic emission, which means the escape of electrons from hot metal. This effect was observed, but not understood, as early as 1884 by Thomas Edison. He noticed in an early electric lamp that a flow of electricity occurred between the hot luminous filament and a cold electrode also sealed in the bulb. Edison showed the phenomenon to a visiting British electrical engineer, W. H. Preece, and paid no more attention to it. Preece took the news to Britain, where the physicist J. A. Fleming (who was later to make the first electron tube) and others showed some interest in it. In 1900 Thomson strongly asserted what proved to be the explanation of this effect, and his pupil O. W. Richardson later elaborated it in detail.

The free electrons in a metal are in continual motion. As the temperature of the metal is raised, the motion speeds up. If the metal is heated sufficiently, the electrons become so agitated as to boil right out past the barrier at the surface.

That barrier is important. Electrons must move very fast indeed to escape from tungsten, the metal of which incandescent lamp filaments are made; tungsten filaments must be heated white-hot to give much thermionic emission. In 1904 the German physicist A. R. B. Wehnelt discovered that if a metal is coated with certain substances, electrons can escape from it at much reduced temperatures. Later, through work at the Bell Telephone Laboratories and elsewhere, it became clear that oxides of barium and strontium are the most suitable coatings, and these are now almost universally used.

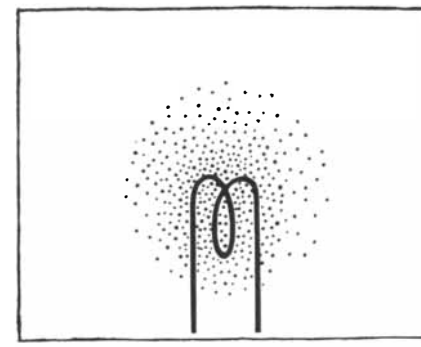
Electron Tubes

We have, then, a ready source of electrons—thermionic emission—and the knowledge that electrons are attracted by a positive electrode and repelled by a negative electrode. How can one make use of this knowledge? The answers were supplied by Fleming in the diode tube and by Lee de Forest in the audion, or triode.

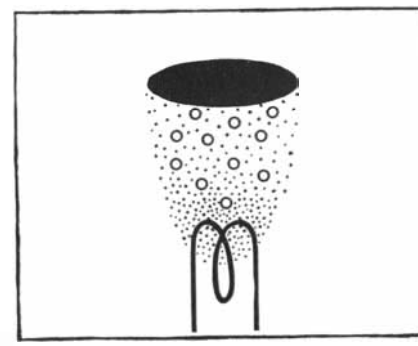
The diode, the simplest of electron tubes, consists of a hot, electron-emitting cathode and a cold, electron-collecting plate that serves as anode. If the plate is made positive with respect to the cathode, electrons will flow to it; if the plate is negative, no current can pass through the tube. Thus the diode can be used as a rectifier to change alternating current to direct current. In your AM radio a tiny diode changes the received signal, a high-frequency alternating current, into a unidirectional current whose strength varies with the sound. Other diodes are used in your radio set to change the alternating current of the house electric supply into the direct current needed to operate other electron tubes.

De Forest's contribution was the introduction of a third element of revolutionary effect. Like the diode, the triode has a hot emitting cathode and a non-emitting anode or plate. Between the two is an open electrode made of fine wire, the grid. The plate is kept positive at all times and the grid somewhat negative at all times. The negative grid repels electrons, but some of them can go to the attracting plate through the interstices of the grid. The number of electrons that reaches the plate per second, and therefore the strength of the plate current, depends on how negative the grid is made. If the grid is made very negative, the stream of electrons is completely blocked and the plate current is turned off entirely. If the grid is only a little negative, the plate current can be quite large. Thus the negative grid acts to control the plate current. The tube can in fact be used as an amplifier, for a small change in the electric potential of the control grid can cause a large power change in the plate circuit. The revolutionary achievement of the triode is this amplification; it has made long-distance communication possible and has given birth to a whole family of negative-grid tubes for a great variety of purposes.

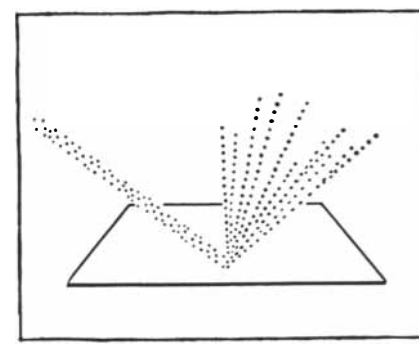
If a condenser and coil are provided between the plate and the grid, one obtains an electric oscillator. The amplifying effect of the tube tends to intensify any swinging disturbance in the circuit, and so produces a sustained electric oscillation. Oscillators are used to generate the radio signals in radio trans-



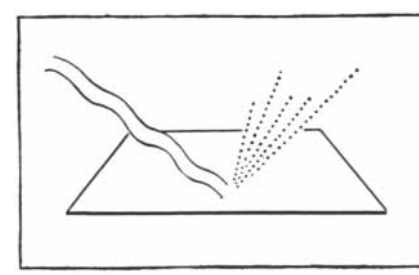
HOT CATHODE is a piece of metal heated so that electrons boil from its surface. Surface can be treated to enhance the emission of electrons.



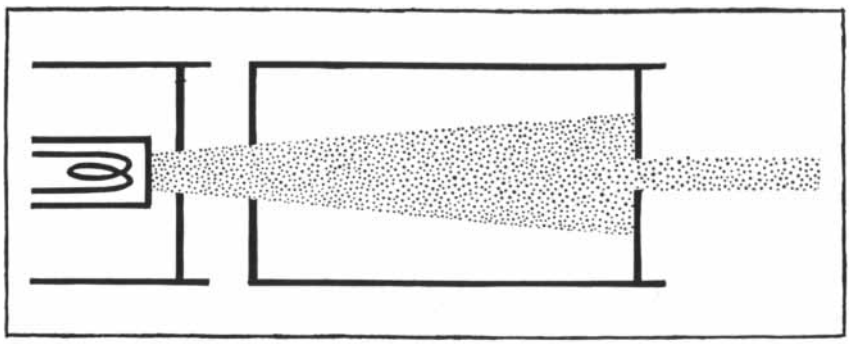
COLD CATHODE yields a few electrons to anode. If tube is filled with gas, electrons produce ions which knock other electrons from cathode.



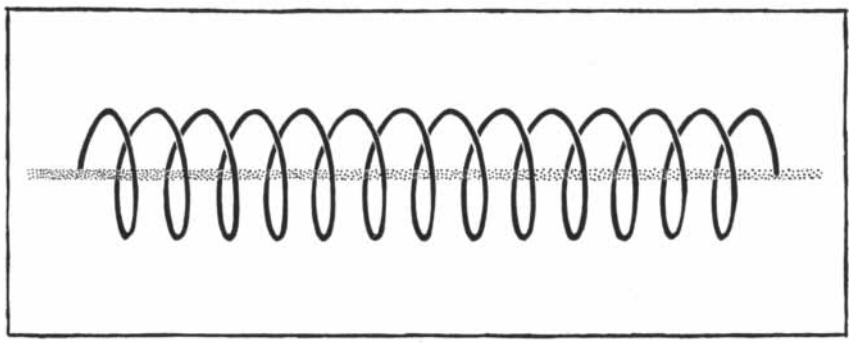
SECONDARY EMISSION occurs when fast-moving electrons strike a metal plate. Incident electron can knock out three secondary electrons.



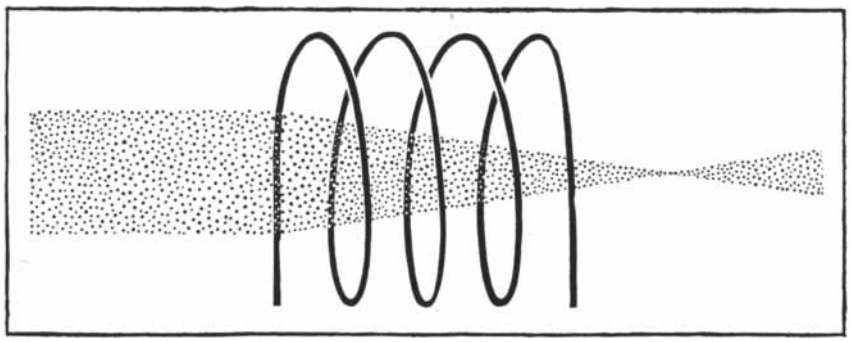
PHOTOELECTRIC EMISSION of electrons occurs when light strikes a photosensitive surface. This effect is utilized in the photoelectric cell.



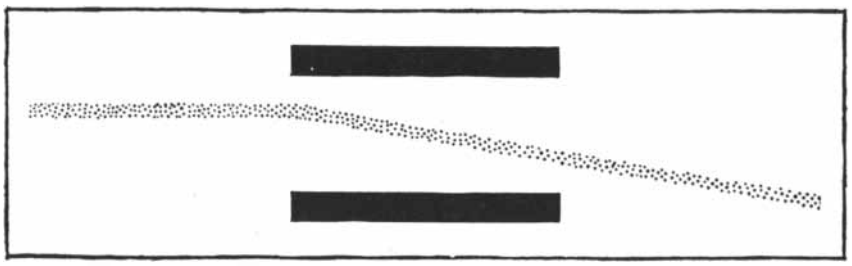
ELECTRON GUN is the fundamental means of producing a beam of electrons. In this schematic drawing the cathode is the electron-emitting surface at the far left. The electrons travel through a hole in the grid and through another hole in the anode. The third hole defines the beam more sharply.



LONG COIL may be used to focus beam of electrons. When current passes through the coil, it is surrounded by a magnetic field parallel to its axis. The field exerts no force on electrons moving parallel to the coil's axis, but electrons crossing the magnetic lines of force are turned back toward the axis.



SHORTER COIL may be used as a magnetic lens to focus electrons. Near the center of the coil the magnetic lines of force are parallel to its axis. Toward the ends of the coil, however, the lines of force bend away from the axis. An electron entering the coil away from the axis is thus forced toward it.



TWO PARALLEL PLATES may be used to deflect an electron beam. If one of the plates is made positive with respect to the other, the electron beam is bent toward the former. The charge on the two plates may rapidly be altered to move the electron beam (*see the tube drawing at the top of page 36*).

mitters, and negative-grid amplifiers intensify these signals before they are sent out.

The triode was the first important electron tube, and its relatives are still the most important and flexible of tubes. The triode itself has of course been greatly refined. In early tubes the electrons came from a white-hot tungsten filament. Now they come from the emissive coating on a dully glowing nickel tube or button, heated by an insulated tungsten spiral. In the early tubes the grid was a coarse structure far from the cathode. In one modern triode the grid has 1,000 wires per inch, each wire about a tenth the diameter of a human hair, and the grid is only one half of a thousandth of an inch from the hot cathode.

In some of the triode's descendants more grids have been added, making the tube a tetrode, pentode, hexode, heptode and so on. The additional grids make it possible to use the negative-grid tube at higher frequencies and increase its versatility and efficiency.

The diode and the triode use a broad flood of electrons which, like water spreading over a surface, avoids the heights (negative electrodes) and rushes down a declivity (toward the positive electrode). But we should remember that electrons can also be channeled in narrow, well-defined beams, and that these can be deflected electrically and magnetically. Surely these facts must be of some technological importance. Indeed they are. In the hands of Ferdinand Braun in Germany and of J. B. Johnson in this country they gave us the cathode-ray tube, the progenitor of today's television picture tube, and Philo T. Farnsworth and Vladimir K. Zworykin of the U. S. added other ingredients to create the tubes used in transmitting television.

Beams

In a television tube an electron gun is used to produce an electron beam. The electrons are emitted by a flat disk coated with emissive material and heated by a tungsten coil. Just beyond the disk a negative electrode with a circular aperture serves, like the grid of the triode, to control the intensity of the electron beam, and helps to focus the beam as well. A positive apertured electrode pulls the electrons through the aperture in the grid electrode and accelerates them to a high speed. Still another aperture limits the size of the beam. The beam that then emerges from the gun is focused to a fine spot by means of a magnetic or electric field, which serves as a "lens."

The electron gun that produces a beam, the magnetic or electric lens that focuses it and electric or magnetic deflectors that bend it form the ingredients

of the cathode-ray tube and of the television picture tube. In these tubes a controlled beam of electrons is focused in a small spot on a fluorescent screen at the end of the tube, and the fluorescent material glows brightly under the impact of the electrons. The deflecting electrodes or coil, placed before the screen, can bend the electron beam and cause the bright spot on the screen to move horizontally or vertically.

In the cathode-ray oscilloscope the electron beam is swept smoothly across the fluorescent screen from left to right, tracing a bright line on the screen. At the same time the beam is deflected up and down according to the voltage in some circuit. Thus an exact picture of the variation of voltage with time can be obtained. The cathode-ray oscilloscope is the experimenter's most valuable diagnostic aid. In the television receiver, as the electron beam sweeps successive lines across the screen the television signal applied to the grid electrode varies the strength of the beam, thereby producing bright or dim spots on the screen; in this way the whole picture is repeatedly painted.

Television pickup or camera tubes, such as the iconoscope and the orthicon, are photoelectric cells that pick up the light image and convert it into electric current. Since the light available is often very faint, a device providing secondary emission of electrons is sometimes used to strengthen the current. The photoelectrons released from the photosensitive surface on which the image is focused by the camera lens are accelerated toward and strike an electrode treated so as to emit three to five secondary electrons for each primary photoelectron that strikes it. In turn, these secondaries can be accelerated to another secondary emitting surface, and so on. By such means the output current can be made a hundred thousand to several million times as great as the original current of electrons expelled from the photosensitive surface, which explains why television cameras can obtain satisfactory pictures in relatively dim light.

The image orthicon is a wonderful example of how the various physical phenomena of electronics can be brought together cooperatively in a technological device. In this tube a camera lens focuses a light image of the scene to be televised on one side of a thin transparent sheet of photosensitive material. Photoelectrons emitted from the other side of the sheet are accelerated by an electric field and focused by a magnetic field on the surface of a second very thin sheet of insulating material. The striking electrons cause a charge pattern on this surface, a pattern which corresponds faithfully in intensity to the light pattern falling on the photoelectric surface. But each electron that strikes causes several electrons to leave, so the pattern is positive rather than negative.

The insulating sheet on which the charge pattern is formed is so thin that the side opposite to that struck by electrons attains essentially the same potential. An electron beam scans this opposite side repeatedly, tracing out the whole surface. The surface takes up just enough electrons from this beam to make up for the secondaries lost on the other side and neutralize the charge on the surface. The rest of the electrons in the beam turn back. Thus as the beam scans the surface the returning current varies in intensity with the charge on the insulating surface and hence with the brightness of the picture. The returning current is amplified by a secondary emission multiplier to form the electric output of the tube.

So far we have considered the production and use of electron beams whose currents are best measured in millionths of an ampere. Can more intense electron beams serve some useful purpose? Of course they can and do, but there is more than electron beams to this story. It takes us into the whole field of microwave radio.

Tubes for Microwaves

The story of radio began with radio waves a few feet long, waves of very high frequency. Soon these were replaced by low-frequency waves miles in length. The generation of these long waves involved large coils and huge condensers. When, somewhat before World War II, experimenters began to work with waves only a few inches long, they had to use entirely new types of circuits, for the coils and condensers necessary to produce such short waves would be hopelessly small, delicate and inefficient.

One of the new devices developed to create microwave oscillations was the cavity resonator. A cavity resonator is a metal enclosure containing alternately a magnetic and an electric field. A change in the magnetic field produces an electric field, and a change in the electric field in turn produces a magnetic field. The electric and magnetic fields repeatedly change in strength and reverse in direction; energy in the resonator is continually transformed from electric energy to magnetic energy and back again, swinging back and forth billions of times a second.

Suppose that a steady electron beam is shot through a cavity resonator and is acted on by the rapidly fluctuating electric field. The electrons passing through are alternately slowed down and speeded up, as the changing electric field retards or accelerates them. As a result, the electrons that have been speeded up overtake the slower ones and form bunches; the originally smooth beam then becomes a fluctuating current.

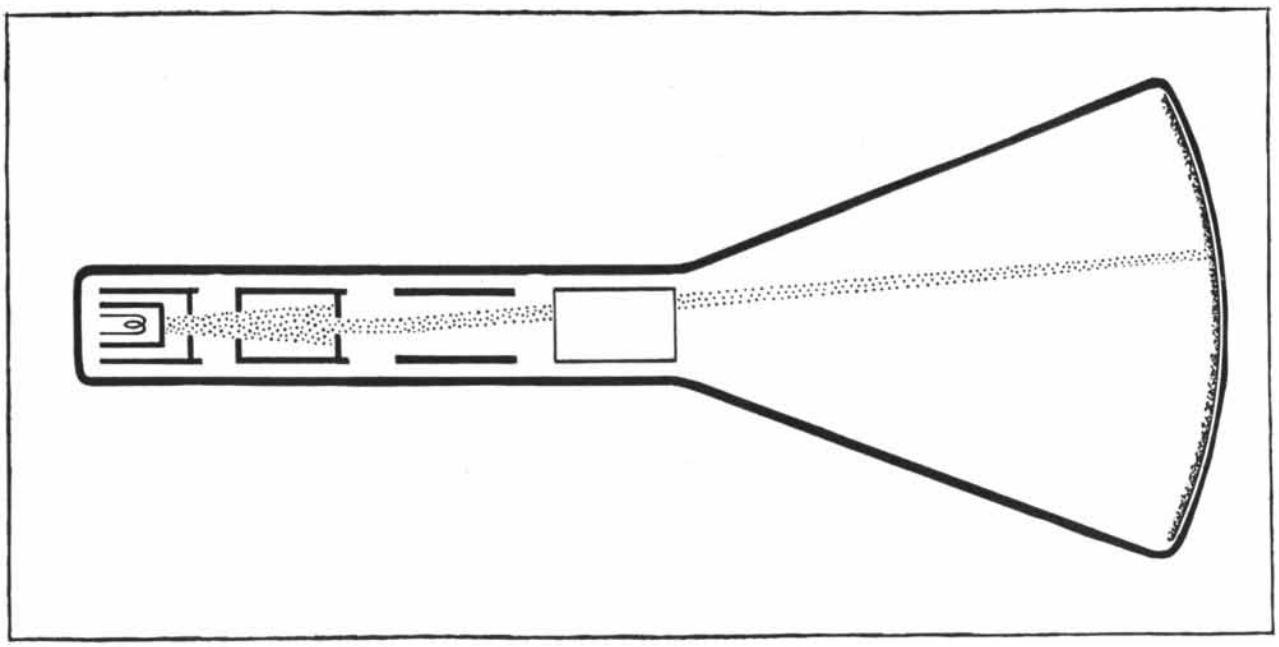
What we have come to in our piecemeal description is the klystron, the earliest of microwave amplifiers and one of the most versatile of microwave tubes. In a klystron amplifier a beam from an electron gun, perhaps focused by a magnetic field, is passed through two cavity resonators. The first resonator, excited by the microwave radio signal to be amplified, has an electric field proportional to the strength of that signal, and this fluctuating field acts to accelerate and retard the electrons in the beam. The beam then leaves the resonator and travels through a drift space in which the speeded electrons overtake the slowed electrons and the beam becomes bunched. When the bunched beam passes through the second resonator, it excites an electromagnetic oscillation and produces an amplified output signal.

During the war klystron oscillators were used in radar receivers. Now they serve as amplifiers in the radio relay link that carries television programs between New York and Boston. In short bursts or pulses klystrons have generated the most powerful radio signals ever made—microwaves having powers as great as 20 million watts!

A more recent microwave circuit is the traveling-wave tube. A stream of electrons is shot down the center of a long helix—a coil of wire much like a stretched door spring. The helix itself receives a microwave radio signal which travels along it at a speed a little slower than that of the electrons. The electric field of the radio signal acts on the electron stream to bunch the electrons into groups of greater than average density. The bunched stream of electrons in turn acts to strengthen the radio wave traveling down the helix. The action may be likened to that of a wind blowing over the surface of a rippled pond and raising the small ripples to sizable waves. The "electron wind" in a traveling-wave tube can multiply the power of the radio wave in the helix as much as 10,000 times.

The traveling-wave tube has even newer relatives, including the "double stream" amplifier. In this device two electron streams of different velocities are intermingled. Between them there takes place an interaction similar to that between the electron stream and the helix of the traveling-wave tube, and the resulting amplification can be even higher than that of the traveling-wave tube.

A more remote relative of the klystron is the wartime magnetron, which made possible microwave radar of very tiny wavelengths (in the centimeter range). The magnetron has resonators in the form of radial slots cut in the inside surface of a thick tubular anode surrounding a central cathode. A cloud of electrons drawn from the central cathode is bent and set into a whirling motion by a magnetic field. This whirling cloud



CATHODE-RAY TUBE may utilize two sets of plates such as those shown at the bottom of page 34 to move an electron beam in three dimensions. At the left end of the tube is an electron gun. To the right of it is one pair of deflection plates. Further along is another pair of plates at right angles to the first. By means of these four plates the beam can be made to paint an image on the fluorescent material which coats the end of the tube.

interacts with a signal in the surrounding circuit much as the long stream of electrons interacts with the radio wave traveling along the helix in the traveling-wave tube. By this means, powerful microwave oscillations can be obtained for short periods—powers of over a million watts lasting perhaps a few ten-millionths of a second.

For the production of continuous power at high frequencies a little short of microwave frequencies, there is another new tube: the resnatron. A recent tube of this type for operation at a frequency of 500 megacycles employs 48 separate electron streams shot through slots which act as grids, and it gives a continuous power of 500 kilowatts.

The tubes described so far are vacuum tubes. There are also modern counterparts of Geissler's gas tubes—gas diodes, gas triodes (called thyratrons) and other types as well. All gas tubes have two features in common. First, when the anode is positive they can easily be turned on by raising the grid or anode voltage a little, but once turned on, current will flow until the anode voltage is reduced to near zero. Secondly, a gas tube of a given size is capable of carrying a much larger current with less loss than is a vacuum tube.

If size and power were the measure of importance, then the most noteworthy of electron tubes would be the type that uses a mercury pool. In this device the cathode is not a hot filament or tube but a little bright spot that skitters over the surface of the pool of mercury. One of the most flexible of mercury-pool tubes is the ignitron. Current flow is initiated by applying a voltage to a resistive igniter electrode which extends into the mercury pool. The discharge can be stopped only by reducing the anode voltage to zero. The most powerful ignitrons are enclosed in metal tanks rather than glass bulbs. They can handle currents of several thousand amperes. Small ignitrons are used extensively in welding equipment. Large mercury-pool tubes, ignitrons and others, are used chiefly to change alternating current into direct current in the operation of electric railways and in the electrochemical industry, particularly in the production and refining of aluminum, magnesium, zinc and copper.

Electron tubes provide our technology with a variety of tools. Sensitive photocells can sense faint lights, and television tubes can seize on and reproduce whole moving scenes. Cathode-ray oscilloscopes can picture the workings of complicated circuits or apparatus. With the development of many special electronic devices, and particularly with the coming of electronic computers, a variety of special tubes have been developed to perform complicated functions. Negative-grid tubes are used in connection with all of these devices to amplify signals, and they perform a wide variety of other functions as well. Finally, under the control of these high-vacuum tubes, thyratrons and ignitrons can handle large currents, turning them on and off quickly, and can control the speed of powerful motors. In another field, vacuum tubes can send out radio and radar signals with powers of thousands and millions of watts.

Perhaps most important, however, electron tubes make it possible to amplify faint signals and to perform complicated operations at a speed and with a precision tremendously beyond the capability of any mechanical contrivance, even the finest instrument or watch.

The Impact of Electronics

Between 1930 and 1949 the annual business in radio tubes, which account for the bulk of the electron-tube industry, in the U. S. went from $120 million to $300 million, and the number of tubes manufactured from 52 million to 230 million. But statistics tell much less about the impact of electronics on our lives than do the radio and television sets in our homes. A world without electronics would be a dumb world to us. It requires a little imagination to recall the pre-radio world. In that world there was no morning weather broadcast to tell one to wear or not to wear a raincoat; there was no following of the day's news hour by hour. If people wanted music in their homes they had to play it, or listen to a tinny phonograph which rasped out coarse sounds and ground up records. They could go to the movies, but the movies were silent, for the sound that goes with the picture today is a product of electronics. The more distant of their friends, relatives and business associates were out of reach by telephone. No public speaker could be heard by an audience larger than could crowd within the reach of his voice.

There was radio of a sort before electronics. There was long-distance tele-

phony, and in dry weather the telephone user could shout from New York to Denver. There were phonographs of a kind. Behind the revolutionary present-day improvements in all these devices is a particular common magic—the magic of amplification. The days before the audion initiated electronic amplification may be likened to the days when a man made his bicycle go by pushing on the pedals. The post-audion days belong with the automobile. The driver who steps on the gas merely controls the power of the machine; he does not push the car along.

In the making of a modern phonograph record the sound generates a tiny electric current, which need do no work at all. An electron-tube amplifier, deriving its power not from the voice or music but from the city electric supply, drives the cutting stylus that forms the groove in the record in a faithful reproduction of the tiny fluctuations of voice or music. Similarly in playing the record the phonograph pickup merely translates the wiggles of the groove into a tiny electric current; it is the powerful output of the amplifier that drives the paper cone of the speaker in and out in a faithful reproduction of the motion of the light stylus in the groove of the record. In telephony the electric current that operates the telephone receiver your listener holds to his ear in Los Angeles is not the current that leaves your instrument in New York. That current has been reproduced by amplifiers many times. In the radio transmitter the tiny current from the microphone controls the power output of amplifiers delivering tens of kilowatts to follow faithfully the small variations that distinguish speaker from speaker.

But amplification is not the sole service performed by the electron tube. It is used to transform low-frequency power into high-frequency power, and this affects our lives in many other ways. By means of high-frequency currents the inside of a person's body, a layer of glue between thick boards, a metal part suspended in an evacuated bulb can be heated in an accurately controlled manner. For the nuclear physicist the electron-tube oscillator produces the high-frequency, high-power voltages by means of which cyclotrons, synchrocyclotrons and linear accelerators speed atomic particles to energies of many millions of volts.

Besides the functions of amplification and production of high-frequency power, electron tubes perform certain other jobs in which their great speed is the main consideration. Electronic devices now are at least 1,000 times as fast as their mechanical counterparts, and inherently they are a great deal faster. Sometimes this speed may be used merely to achieve an economy in an old function. For example, electronic equipment in telephone exchanges, in place of the present electromechanical mechanisms, may give us speedier service in the future. The speed of electronic circuits can also lead to entirely new results. Many of the functions necessary in a television set are of this sort; they are neither amplification nor mere production nor control of high-frequency currents, and these functions must be performed so speedily that only electron tubes can do them. In another field, that of computation, electronic calculating machines have been used to solve problems in applied mathematics which would never have been attempted with electromechanical machines. In still another field, electron tubes are essential in the measurement and control of nuclear reactors.

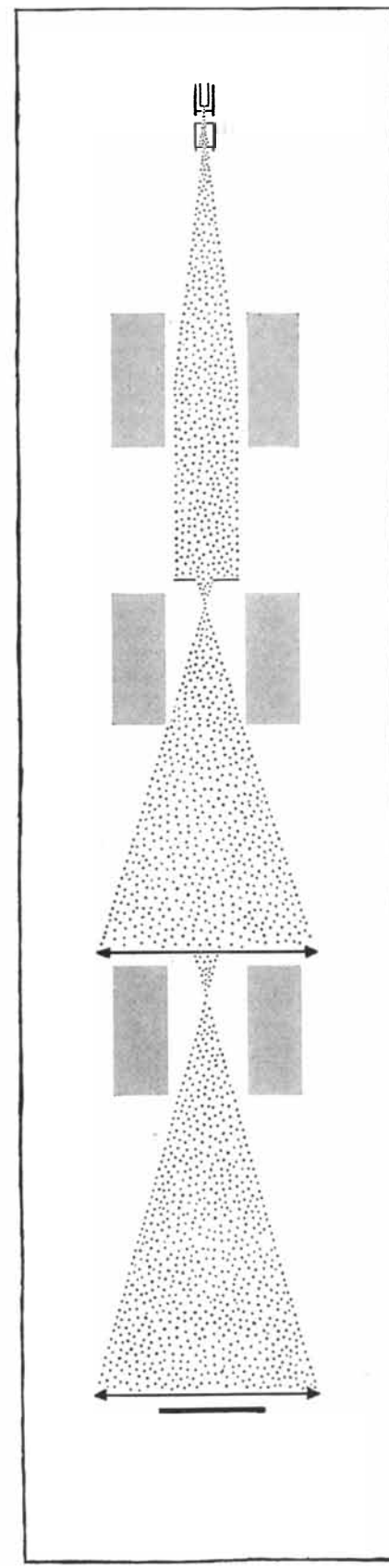
Year by year the scope of electronics becomes broader and the functioning of electronic circuits becomes more complex. New electron tubes continually turn the well-tried behavior of electrons to new and fruitful uses.

The Future

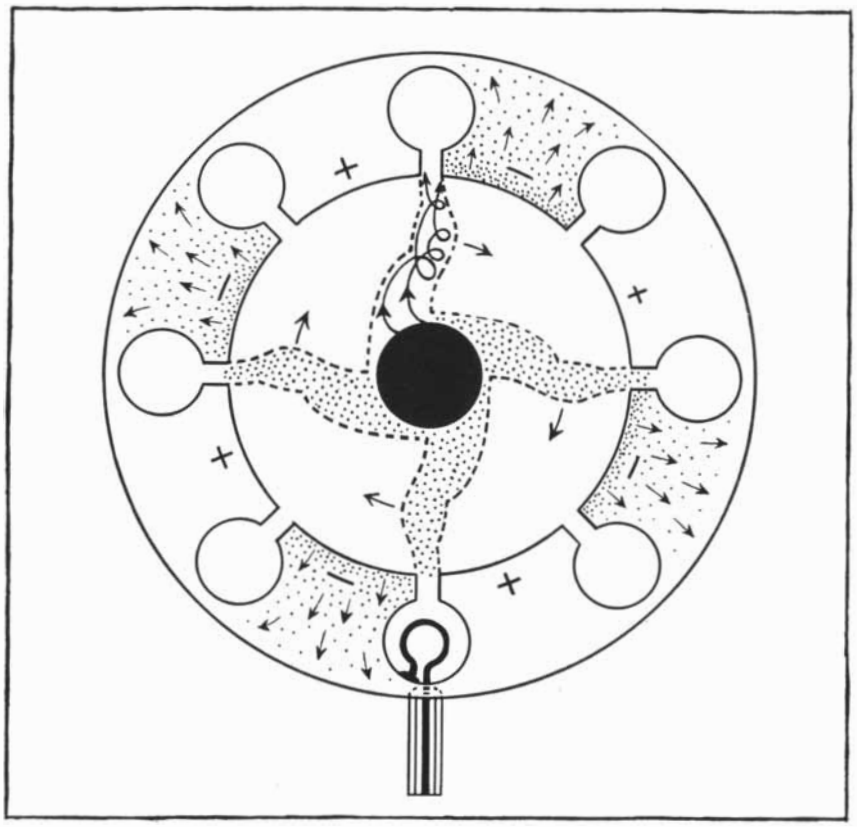
It is not always easy in these days of rapid advance to distinguish what has already been achieved from what is yet to come. Sometimes the newspapers herald almost as an accomplished fact a giant electronic brain that has only passed from being a gleam in an enthusiastic worker's eye to being a chronic pain in a discouraged worker's neck. What predictions can be made about future developments in electronics?

Some things we can see rather clearly in a general way. There will certainly be commercial color television, though we do not know its exact form. There will surely be more communications of a wider variety, and television for purposes other than home entertainment will be a part of this. Perhaps the first of these new applications will be television conferences among widely separated persons. Perhaps eventually new advances will make television with the telephone an economic possibility. All of this depends on the development of ways to send signals long distances more cheaply. It is not yet clear whether or in what degree this will be done by microwave radio from tower to tower, over wires or by radio waves of frequencies of perhaps 50 billion cycles per second traveling through a pipe called a waveguide.

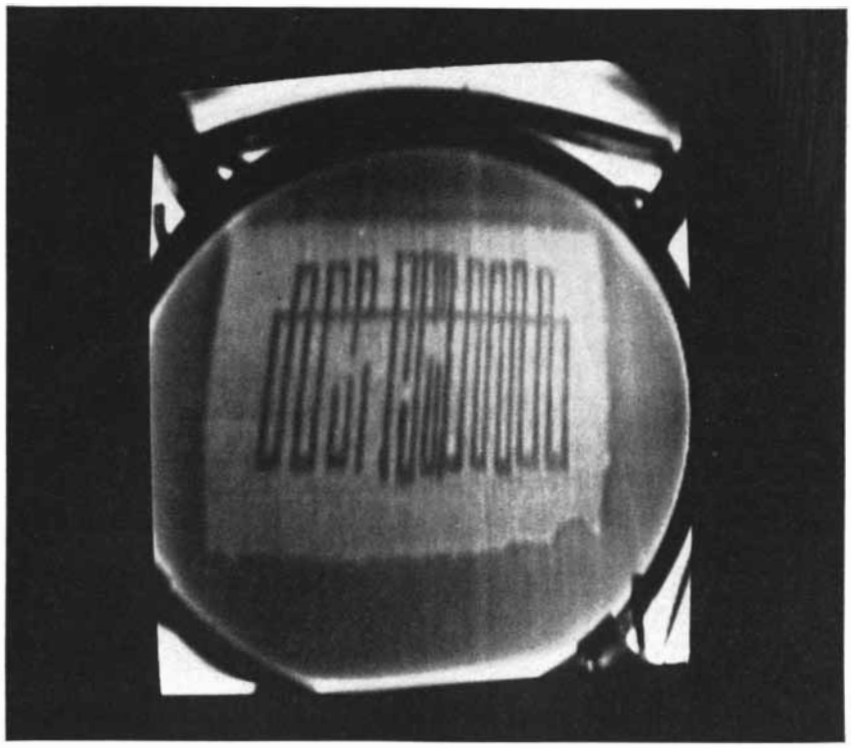
We may expect more vacuum tubes in devices such as business machines to give speedier operation. Electron tubes will appear in a variety of unexpected places; they have already shown up in the control systems of toy trains. Light-operated and perhaps radio-operated devices will appear with increasing commonness. Household devices may incorporate electron tubes as they become increasingly automatic.



ELECTRON MICROSCOPE utilizes several focusing coils to manipulate electron beam and produce vastly enlarged image of specimen.



MAGNETRON has resonant cavities in a metal ring. Around the ring is established a magnetic field whose lines of force are perpendicular to this page. The electrons describe curved paths between cathode (*center*) and ring, and give up their energy by interacting with electric field of cavities.



MEMORY TUBE, developed by Andrew V. Haeff of the Naval Research Laboratory, is a memory device for electronic computing machines. The tube can remember either numbers or pictures for hours or days, and reproduce them on demand. On the face of tube is a meaningless test pattern.

Beyond such matters lie possibilities whose realization may be governed more by economic and political considerations than by mere technical feasibility. Here prophecy can concern itself only with what could be, not what will be.

It is clear, for instance, that business machines and wires make possible a far-flung enterprise—a bank or chain of stores—with all its records and accounting concentrated in one center. New information, wherever filed, would be instantly available at any branch of the chain. In the case of a bank, we can imagine that an electronic auditor might ring an alarm in New York when a critical loan that could break the camel's back went bad in some remote hamlet. We can imagine branch stores that would merely exhibit samples, deliveries being made quickly from a central location; information as to whether an item was in or out of stock would be available at the branch in less time than it would take a clerk to hunt on a shelf.

And what of the miracle aspects of electronics? Will we have machines that respond to the human voice, an electronic fourth at bridge, an electronic chess opponent? Will electronic devices compose music as well as reproduce it? This is largely an economic question. Who, we may ask, will subsidize how many smart people to spend how much money in achieving such things?

Finally, what further contributions can we expect the technology of electronics to make to science? It has already helped the advance of knowledge in many branches, not only physics but also astronomy, chemistry, biology. Without electronic apparatus, electronic frequency standards, sensitive measuring equipment, electronic recording devices, photocells for measuring light intensity, particle accelerators, large-scale computers and the fast, cheap long-distance communication which electronics has provided to all sciences, much of the progress that these sciences have made would have been impossible.

I am thinking, however, of another more direct sort of contribution that work on electron tubes has made, and might perhaps make in a greater degree, to astronomy and physics. This has to do with the fundamental problem of the interaction between charged particles and electromagnetic fields. It involves, for example, questions about solar radiation.

Electronics and the Sun

It has long been known that a hot body emits a wide range of electromagnetic radiation: light, heat and, according to accepted and well-proved theory, radio waves as well. The hotter the body, the more intense the radiation emitted. Now man has always been strikingly aware of the light and heat emitted by so large and hot a body as

the sun, but until recently the radio radiation from the sun escaped detection. In 1943 Grote Reber of Wheaton, Ill., using a receiver tuned to two meters, detected radio waves from the sun. In 1946 G. C. Southworth of the Bell Telephone Laboratories published measurements of solar microwave radiation at wavelengths of 10 centimeters and three centimeters. Southworth's measurements furnished an estimate of the sun's temperature independent of that by earlier light and heat measurements, and it roughly confirmed these earlier measurements, placing the sun's surface temperature at about 6,000 degrees Kelvin.

Very shortly afterward, however, a report published in *Nature* changed this picture in a startling way. Workers in Australia, on the basis of new measurements of the rising sun at a wavelength of 1.5 meters, found that the sun had a steady background temperature of one million degrees, with much higher bursts which they proved to be associated with sunspots. There is still a great deal of speculation concerning this intense radiation. Apparently it comes from the sun's tenuous outer atmosphere, the corona, which is transparent to light, heat and short microwaves but opaque to radiation of longer wavelengths.

Astronomers and astrophysicists believe that the million-degree background radiation represents the true temperature of the corona, but they are at a loss to explain why the corona is so hot or what causes the bursts of higher intensity radiation. Physicists familiar with the intense radio waves produced by the interaction of charged particles with electric and magnetic fields in magnetrons have suggested that these same ingredients, known to be present in sunspots, may account for the sun's bursts of intense radiation. In 1947 D. F. Martyn of Australia and Joseph S. Schlonsky of the U.S.S.R. proposed that the bursts might be explained by the phenomenon known as "plasma oscillation," first observed in gas tubes in 1929 by Irving Langmuir and Lewi Tonks. Plasma oscillation is a kind of oscillation of charged particles which does not require the presence of a magnetic field. Others have suggested that the solar bursts may represent types of interactions between clouds of charged particles in relative motion such as occur in traveling-wave tubes, particularly double-stream amplifiers, and which are related in a way to plasma oscillations. It is, for instance, attractive to think that perhaps the huge clouds of ionized gas ejected from the sun as solar prominences may, in rising and falling through the ionized solar atmosphere, produce just the signals that have been observed.

I think that a few years ago physicists would have said that Maxwell's equations and the laws of motion summed up all the interesting aspects of the interaction of charges with electromagnetic fields. Now the phenomena newly observed in the sun, which may be a particular case of such interactions, present some new questions that are very interesting indeed.

A theoretical treatment of the solar phenomena is, alas, extremely difficult. The astrophysicists cannot easily check their theories; indeed, the theories are at present scarcely in a condition to be checked. On the other hand, physicists and engineers who work in the more limited field of the interactions in electron tubes at least have a ready check of their theories, and they may actually be dealing with the same phenomena as the astrophysicists. The theories of interactions between clouds of charged particles in electron tubes and in gaseous clouds are essentially the same, and both are closely related to the theory of other physical phenomena. Among these one can mention the magneto-hydrodynamics of charged particles proposed by the Swedish cosmologist H. Alfven, the propagation of radio waves through the ionosphere, the operation of such alternating-current machines as induction generators, and perhaps various supersonic phenomena, the instability of laminar flow and various statistical problems of astronomy. An adequate comparison of these fields might simplify matters for all concerned.

Hence one might expect a cooperative effort by the workers in electronics and the physicists. Unfortunately, there seems to be little contact between the various groups. Such contact may be established in the future. At all events, the workers on electron tubes, though one stage removed from the field of pure science, can feel that they have helped in some measure to advance matters of a more philosophical nature.

J. R. Pierce has made important contributions in the fields of electron multipliers, electron focusing and microwave electron tubes. He is the author of The Theory and Design of Electron Beams *and numerous popular articles.*

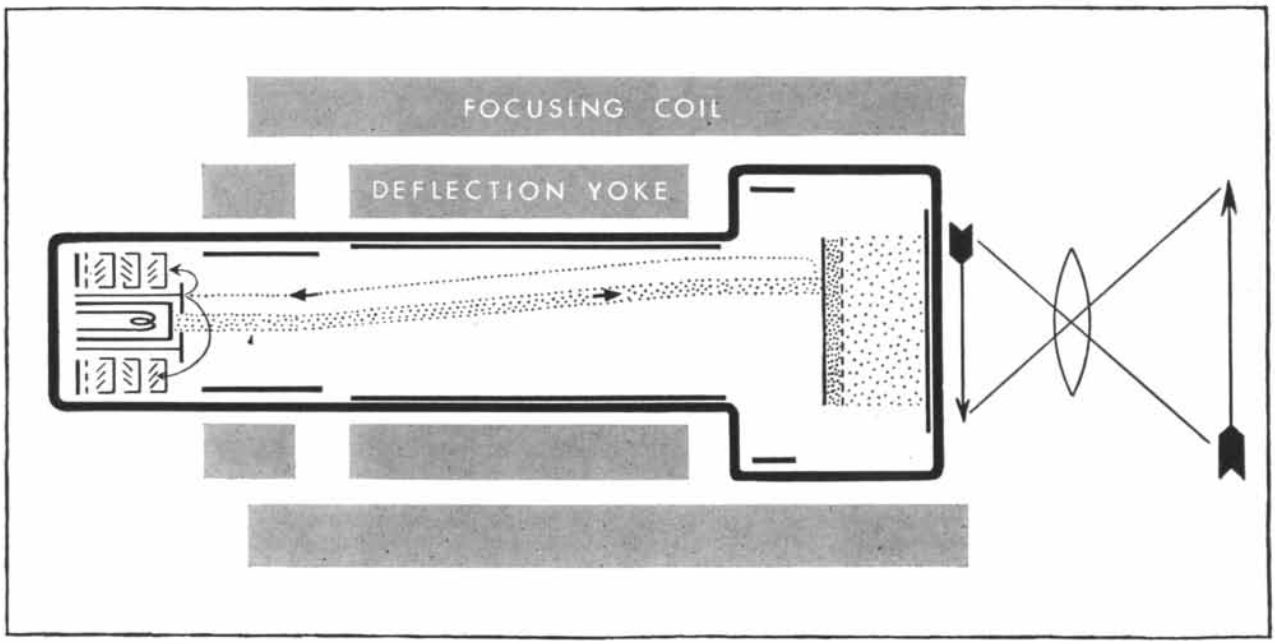


IMAGE ORTHICON is a television camera tube. At right end of tube an image is focused on a photoelectric surface. Electrons emitted from the surface in the pattern of the picture are then amplified by secondary emission. Part of an electron beam scanning a plate charged by these secondary electrons is turned back toward its source. The returned beam is amplified to yield an electric reproduction of the original image.